Experimental lab, test case 1
Calibration of a load cell

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General Information

Report for the first test case of the experimental laboratories within the course of Fluids Labs, by G. V. Messa, Politecnico di Milano.

1 Introduction

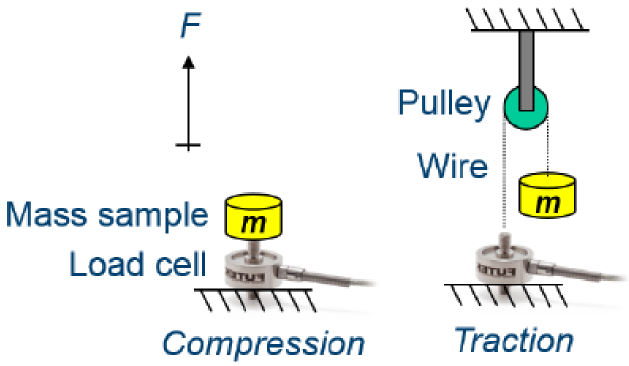

Figure 1: Load cell representation

The load cell is an instrument for measuring a force, which produces an electrical output (voltage) which is approximately proportional to the applied force. In order to estimate the value of a force with a load cell, it is necessary to determine the transfer function from voltage to Newton. The transfer function is obtained by using mass samples whose weight force F* is accurately known. This operation can sometimes be called calibration of the load cell.

2 Case description

Our calibration is carried out basing on the following given data and settings information:

- Each mass sample is applied to the load cell for a few seconds and the corresponding electrical output is recorded (the sampling frequency is $f_s = 100Hz$). This produces a noisy signal like the one shown in Figure 2.

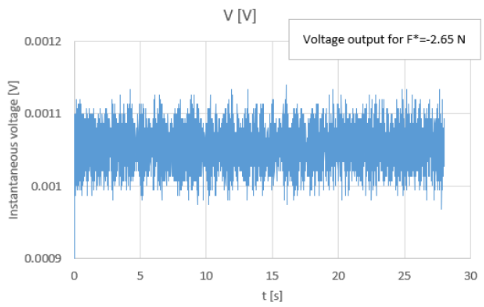

Figure 2: Electrical signal

- The voltage output histories and the corresponding values of the reference force, F^*, are listed in the table 1 and are provided in the form of MATLAB workspaces. Each workspace contains the vector of the readings in Volt. In the table, the sign of F* is as presented in the sketch, namely, $F^* > 0$ when the force is directed upwards, and $F^* < 0$ when it is directed downwards.

Table 1: Force Calibration Results

TestID	F* [N]	TestID	F* [N]
calibr01	0.000	calibr09	-5.598
calibr02	-0.314	calibr10	-10.501
calibr03	-0.411	calibr11	0.126
calibr04	-0.695	calibr12	1.097
calibr05	-0.891	calibr13	2.078
calibr06	-1.186	calibr14	4.039
calibr07	-1.676	calibr15	8.942
calibr08	-2.656	calibr16	13.845

We would like to determine the **transfer function** and **quantify the uncertainty** of the instrument.

Question 1

Question

The noisy behavior of the voltage signal is due to the variability of the electric output. **The electric noise must be filtered out before finding the values of V_0 which are to be correlated with F* through the transfer function.**

This is achieved by calculating the cumulative average plots of the instantaneous voltage output. Such plots show, for each time t_i, the average voltage output from 0 to t_i, with the time on the horizontal axis in log-scale, and they look as in the example in Fig. 3. We calculated the time window for each calibration sample as $\Delta t = \frac{1}{f_s} n$ where n is the sample length.

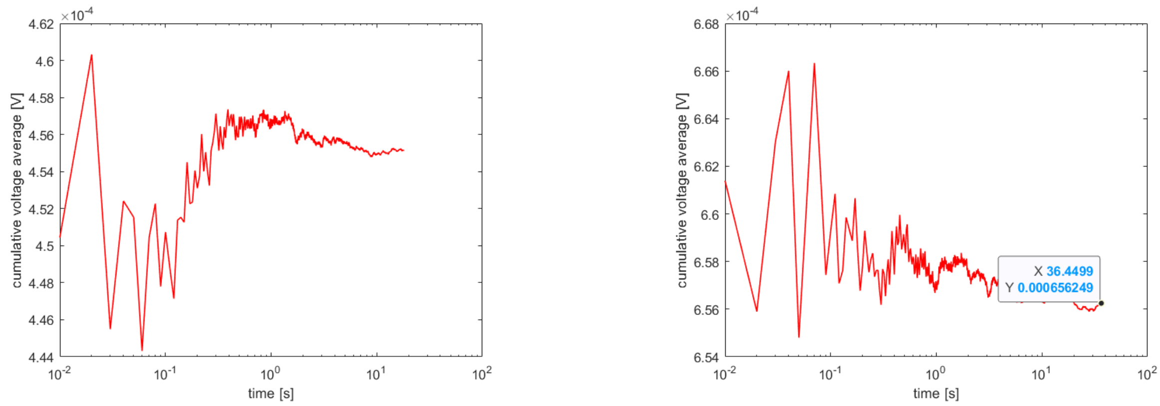

Figure 3: Voltage Cumulative Average versus Time examples.

In order to filter out the noise, we implemented a MATLAB code that, for each calibration test, follows these steps:

- Calculation of the cumulative average voltage.
- Semilogx plot to qualitatively evaluate whether the considered sample reaches convergence.
- Finding the most accurate V_0 value and the associated stabilization time.

In order to reach a more accurate result, considering the small local oscillations and noises we can observe in the plots, we decided to use a moving average to compare the trend of the cumulative mean, detect stabilization considering relative changes between cumulative average elements and only if the relative change remains below a tolerance for consecutive steps.

The results we obtained can be observed in Tab. 2:

$F^*(given)[N]$	0.000	−0.314	−0.411	−0.695	−0.891	−1.186	−1.676	−2.656	−5.598	−10.501	0.126	1.097	2.078	4.039	8.942	13.845
V_0	-2.722×10^{-5}	1.008×10^{-4}	1.363×10^{-4}	2.490×10^{-4}	3.341×10^{-4}	4.551×10^{-4}	6.562×10^{-4}	1.054×10^{-3}	2.252×10^{-3}	4.254×10^{-3}	-7.818×10^{-5}	-4.759×10^{-4}	-8.746×10^{-4}	-1.677×10^{-3}	-3.678×10^{-3}	-5.671×10^{-3}
Stability Time	26.00	53.00	21.00	18.00	32.00	18.00	37.00	28.00	20.00	11.93	62.00	37.00	49.00	41.25	23.73	10.29

Table 2: Results of the noise filtering

A gross estimate of the time of acquisition required to filter out the electric noise was also obtained, taking the maximum value among the stability time values we obtained for each test.

Question 2

Question

Find out the **linear coefficient** b **and** m, in the relation $\mu_{V_0} = mF^* + b$, where μ_{V_0} is the V_0 limiting mean.

We note that the values of V_0 are, in themselves, random. In fact, repetition of the same test produces different values of V_0. The formula which estimates the limiting mean of the V_0 values, μ_{V_0}, as a function of the "reference" force value, F^*, can be derived by linear regression of the (F*-V_0) pairs. We could find b and m values by solving a **least squares system**:

- $b = -2.8934 \times 10^{-05}$.
- $m = -0.00040771$.

Question 3

Question

Provide an **estimate of the uncertainty** associated with the force estimate $\tilde{F}$.

Our practical interest is in a formula which, given a voltage reading V_0, provides an estimate of the corresponding "true" force value F. This formula is called (linear) **transfer function**, and it can be obtained by rearranging the previous limiting mean equation, as follows: $\tilde{F} = \frac{V_0 - b}{m}$. For a given V_0, the formula here above does not produce the real value of F, but just an estimate $\tilde{F}$. This is due to the random nature of the measurement process (note that, in principle, the same V_0 could correspond to every possible F). We now would like to provide an estimate of the uncertainty associated with the estimate $\tilde{F}$, that is, we would like to find U such that, for every V_0, the corresponding force lies within the range $\tilde{F} \pm U$.

- The first approach is to set U as the maximum absolute difference between $\tilde{F}$ and F^* for all 16 calibration cases. According to our calculations, in this case the uncertainty value is $U_1 = 0.0134N$.
- A second approach is to refer to the confidence intervals. For a perfect Gaussian PDF, 95% of the readings falls in the range $\mu \pm 2\sigma$. According to the theory of linear regression, we can estimate U at a 95% confidence as $2s_f$, where $s_f^2 = \frac{1}{N-2}\sum_{i=1}^{N}(\frac{V_i - b}{m} - F^*)^2$ and N is the number of calibration tests. According to our calculations, in this case, the uncertainty value is $U_2 = 0.0112N$.

The estimate we obtain in the second case is clearly lower: it is normal that there are true F^* that are more far from the estimate than others, while the second way of computing U takes into account the distance between the estimate and every ”true” value, so generally speaking the estimate is good with respect to all the tests made.